# Neutrino energy resolution improvement for NOνA
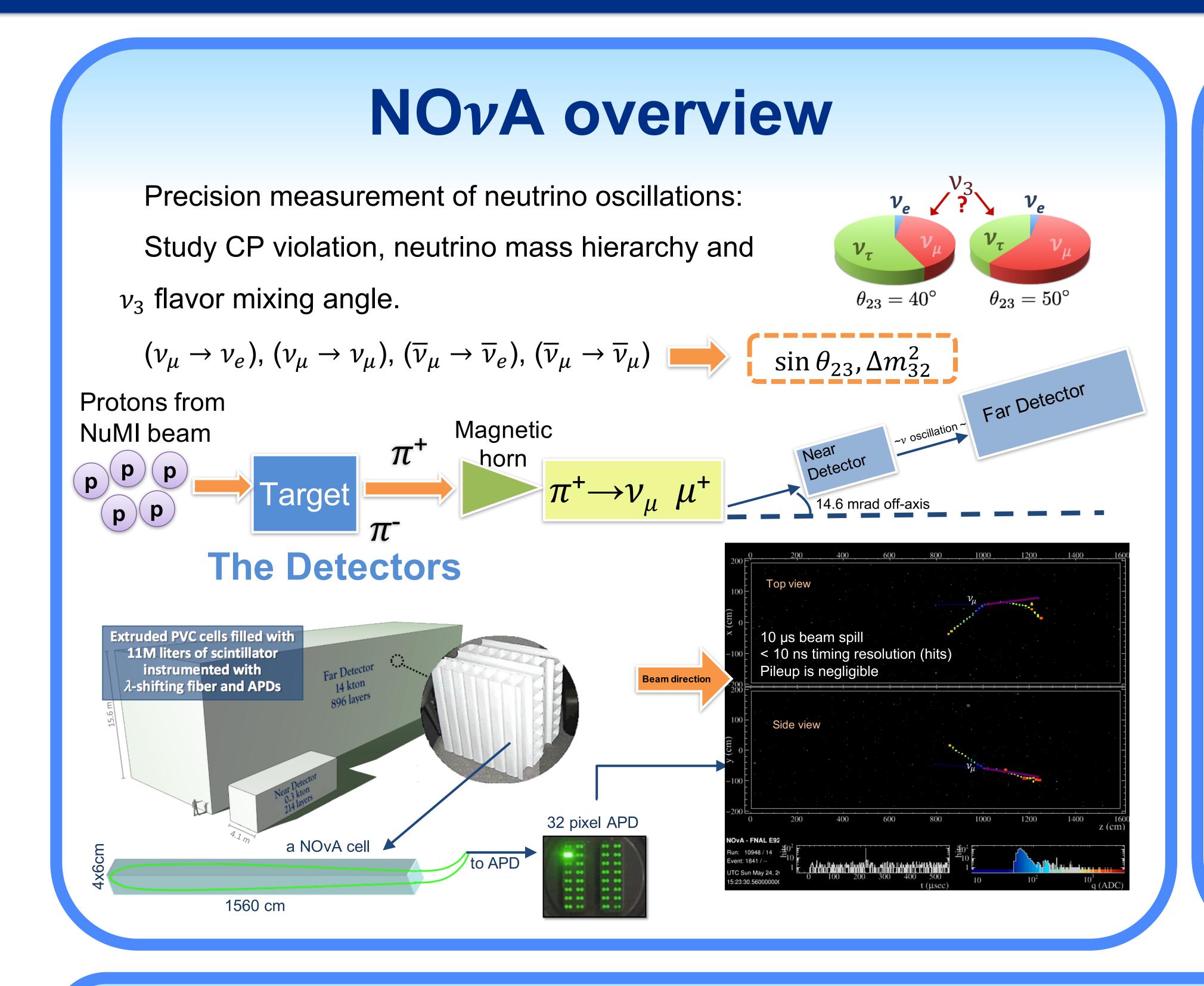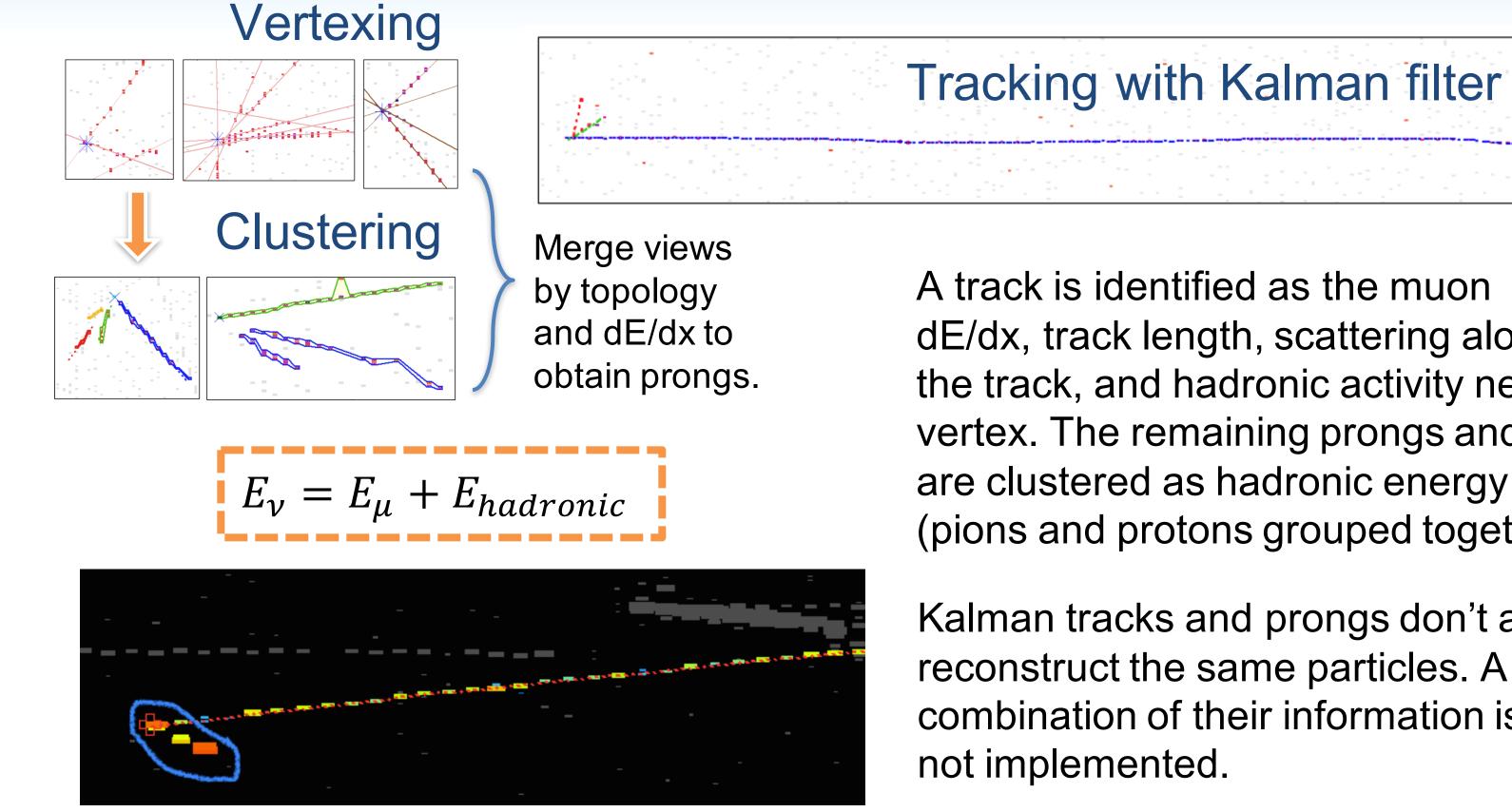
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## NOνA overview

Precision measurement of neutrino oscillations:

Study CP violation, neutrino mass hierarchy and $\nu_3$ flavor mixing angle.

$(\nu_\mu \rightarrow \nu_e), (\nu_\mu \rightarrow \nu_\mu), (\overline{\nu}_\mu \rightarrow \overline{\nu}_e), (\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$ ⟶ $\sin\theta_{23}, \Delta m^2_{32}$

$\nu_3$ ?  $\nu_e$  $\nu_\mu$  $\nu_\tau$

$\theta_{23} = 40°$   $\theta_{23} = 50°$

Protons from NuMI beam

p p p p p p

Target → $\pi^+$ / $\pi^-$

Magnetic horn → $\pi^+ \rightarrow \nu_\mu \ \mu^+$

Near Detector → ν oscillation → Far Detector

14.6 mrad off-axis

### The Detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

Far Detector 14 kton 896 layers

a NOνA cell
4x6cm
1560 cm
to APD
32 pixel APD

Top view
10 µs beam spill
< 10 ns timing resolution (hits)
Pileup is negligible

Side view

Beam direction

## Neutrino energy reconstruction

### Vertexing

### Clustering

Merge views by topology and dE/dx to obtain prongs.

Tracking with Kalman filter

A track is identified as the muon by dE/dx, track length, scattering along the track, and hadronic activity near the vertex. The remaining prongs and hits are clustered as hadronic energy (pions and protons grouped together).

$E_\nu = E_\mu + E_{hadronic}$

Kalman tracks and prongs don't always reconstruct the same particles. A combination of their information is still not implemented.

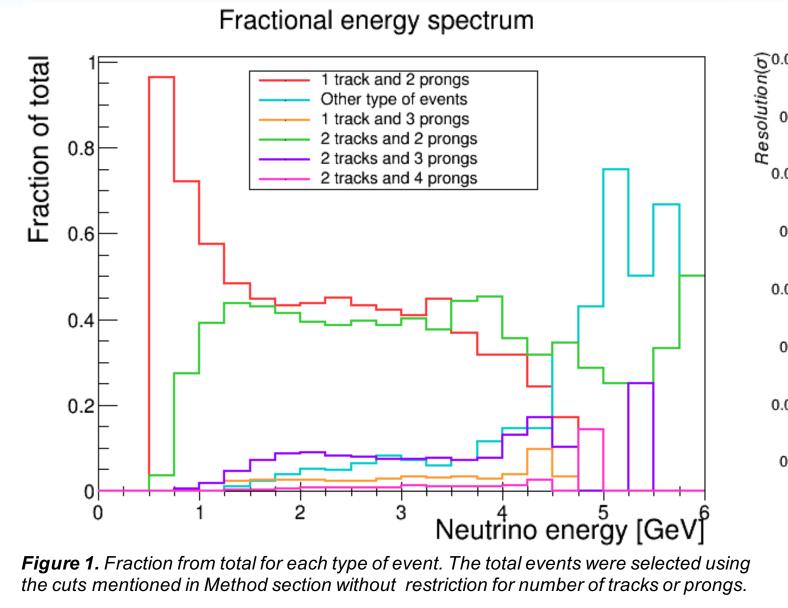The resolution of $\Delta m^2_{32}$ and $\sin\theta_{23}$ is dependent on the energy reconstruction. A low resolution reduces the precision of the measurements; therefore, an improvement in the energy resolution is relevant for the experiment goals.
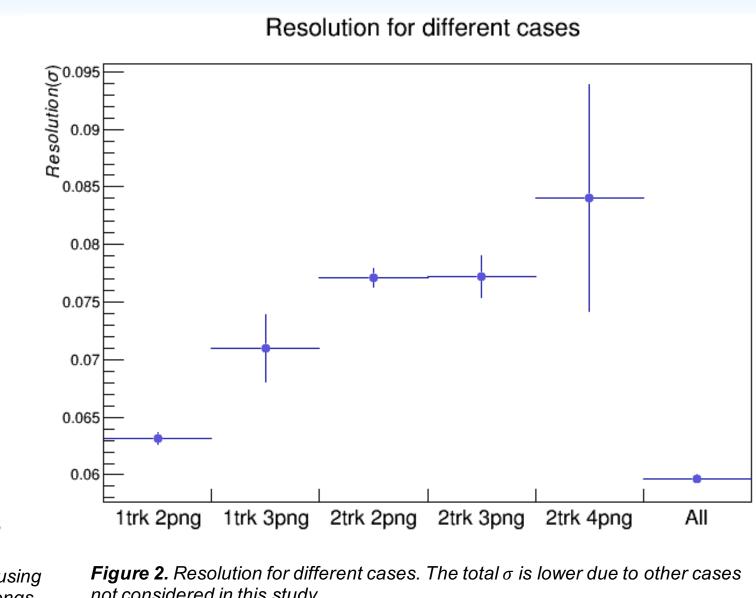
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$
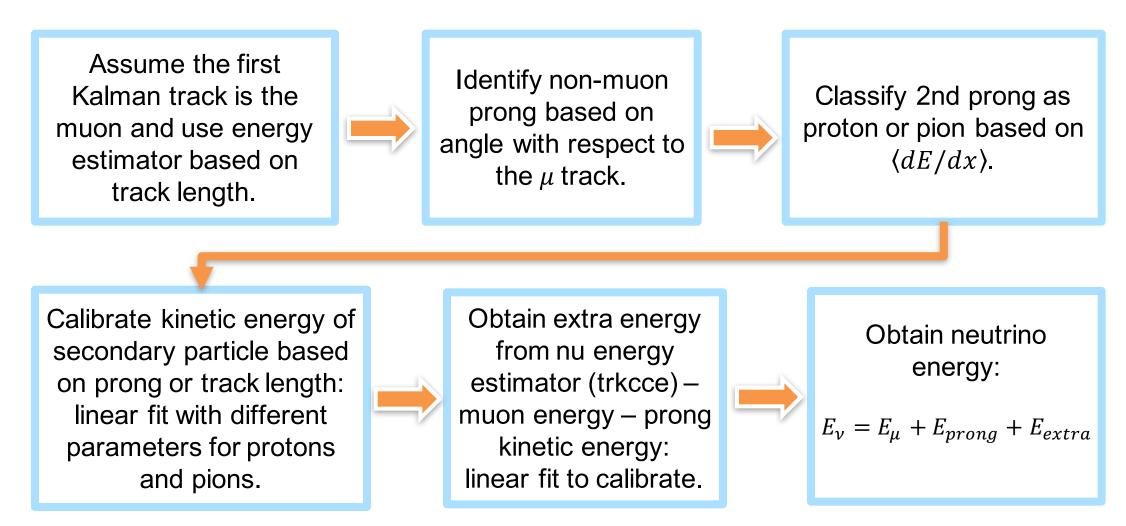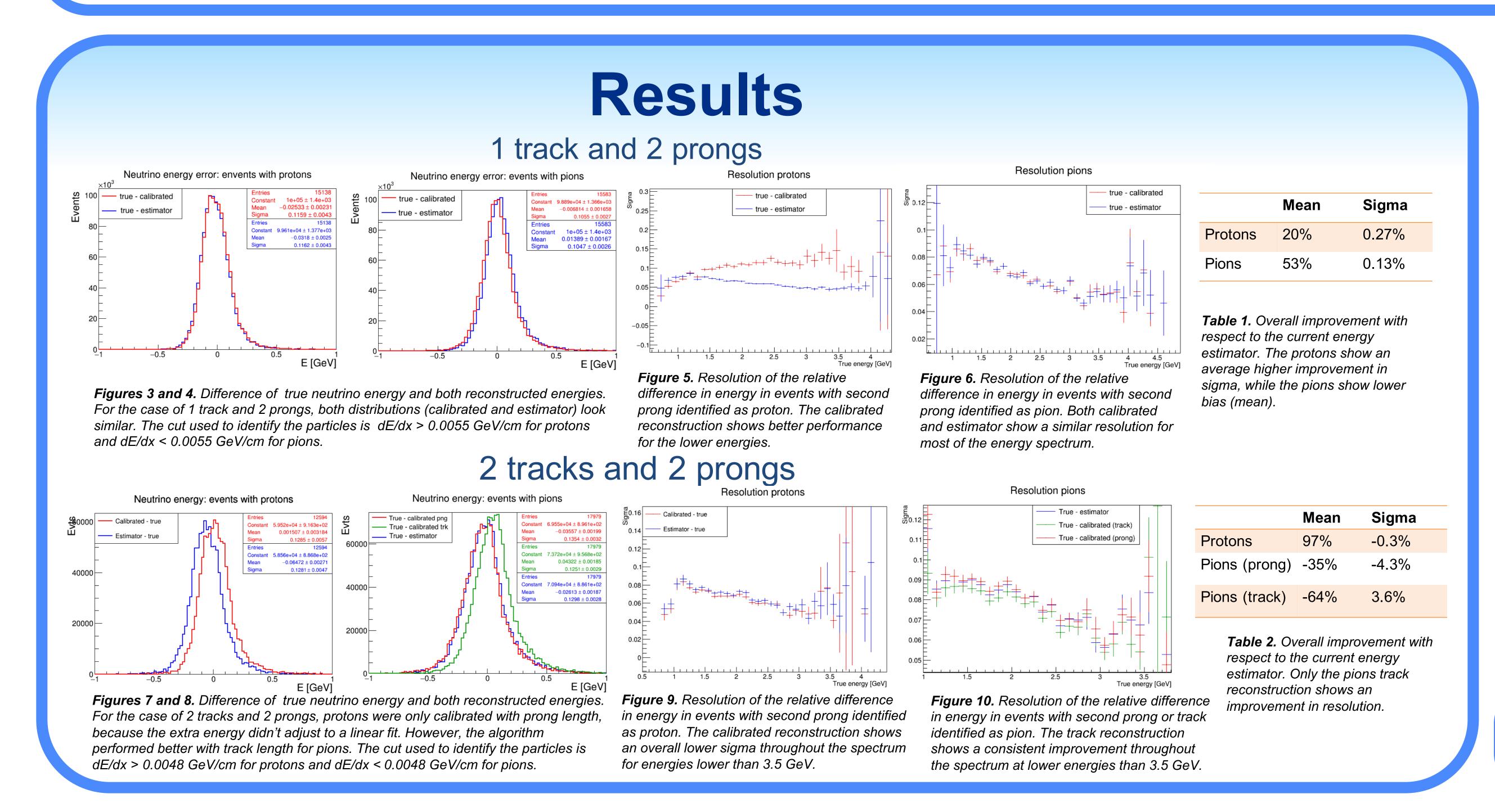
## Method

* Improve resolution by determining the energy estimation for specific types of events: **1 track - 2 prongs**; 1 track - 3 prongs; **2 tracks – 2 prongs**; 2 tracks – 3 prongs.
* Cuts for: minimum number of hits, all tracks and prongs close to vertex, minimum length of tracks and prongs
* Use Monte Carlo simulation to calibrate estimation with true energy of neutrinos.
* Instead of grouping everything that is not a muon in a hadronic shower, try to identify the remaining tracks and prongs as single particles.

*Figure 1. Fraction from total for each type of event. The total events were selected using the cuts mentioned in Method section without restriction for number of tracks or prongs.*

*Figure 2. Resolution for different cases. The total σ is lower due to other cases not considered in this study.*

### Algorithm for 1 or 2 tracks and 2 prongs

Assume the first Kalman track is the muon and use energy estimator based on track length. → Identify non-muon prong based on angle with respect to the µ track. → Classify 2nd prong as proton or pion based on ⟨dE/dx⟩.

Calibrate kinetic energy of secondary particle based on prong or track length: linear fit with different parameters for protons and pions. → Obtain extra energy from nu energy estimator (trkcce) – muon energy – prong kinetic energy: linear fit to calibrate. → Obtain neutrino energy: $E_\nu = E_\mu + E_{prong} + E_{extra}$

## Results

### 1 track and 2 prongs

*Figures 3 and 4. Difference of true neutrino energy and both reconstructed energies. For the case of 1 track and 2 prongs, both distributions (calibrated and estimator) look similar. The cut used to identify the particles is dE/dx > 0.0055 GeV/cm for protons and dE/dx < 0.0055 GeV/cm for pions.*

*Figure 5. Resolution of the relative difference in energy in events with second prong identified as proton. The calibrated reconstruction shows better performance for the lower energies.*

*Figure 6. Resolution of the relative difference in energy in events with second prong identified as pion. Both calibrated and estimator show a similar resolution for most of the energy spectrum.*

|  | Mean | Sigma |
|---|---|---|
| Protons | 20% | 0.27% |
| Pions | 53% | 0.13% |

*Table 1. Overall improvement with respect to the current energy estimator. The protons show an average higher improvement in sigma, while the pions show lower bias (mean).*

### 2 tracks and 2 prongs

*Figures 7 and 8. Difference of true neutrino energy and both reconstructed energies. For the case of 2 tracks and 2 prongs, protons were only calibrated with prong length, because the extra energy didn't adjust to a linear fit. However, the algorithm performed better with track length for pions. The cut used to identify the particles is dE/dx > 0.0048 GeV/cm for protons and dE/dx < 0.0048 GeV/cm for pions.*

*Figure 9. Resolution of the relative difference in energy in events with second prong identified as proton. The calibrated reconstruction shows an overall lower sigma throughout the spectrum for energies lower than 3.5 GeV.*

*Figure 10. Resolution of the relative difference in energy in events with second prong or track identified as pion. The track reconstruction shows a consistent improvement throughout the spectrum at lower energies than 3.5 GeV.*

|  | Mean | Sigma |
|---|---|---|
| Protons | 97% | -0.3% |
| Pions (prong) | -35% | -4.3% |
| Pions (track) | -64% | 3.6% |

*Table 2. Overall improvement with respect to the current energy estimator. Only the pions track reconstruction shows an improvement in resolution.*

## Conclusion

* The method did improve the energy resolution for the case of 1 track and 2 prongs by 0.13% in events with secondary particles identified as pions and 0.27% for the identified as protons.
* For the case of 2 tracks and 2 prongs, events with pions improved the resolution by 3.6 % using track reconstruction.
* There is a separation of particles in ⟨dE/dx⟩, which helps improve the kinetic energy estimation based on the particle.
* However this can be improved by implementing a 2D cut, such as ⟨dE/dx⟩ vs. calE.
* The case of 1 track and 2 prongs is in general well reconstructed by the algorithm, so the study and improvement of the algorithm for more complex events, such as 2 tracks and 2 prongs, will be of interest.

### Reference

R. Patterson. *First Oscillation Results from NOνA.* Joint Experimental-Theoretical Seminar, Fermilab, August 6, 2015.

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